Spin-orbit Phenomena in Non-centrosymmetric Magnetic Multilayers(Abstract_要旨)

AUTHOR(S):

Ham, Woo Seung

（ 続紙 1 ）

京都大学	博 士 （ 理 学 ）	氏名	咸　佑承(Woo Seung Ham)
論文題目	Spin-orbit Phenomena in Non-centrosymmetric Magnetic Multilayers (反転対称性の破れた磁性多層膜におけるスピン―軌道現象)		

（論文内容の要旨）

In this thesis, the spin-orbit phenomena, mainly about SOT and DMI in various magnetic multilayers and superlattices are investigated. The spin torque generated by the charge-to-spin conversion can be investigated by means of AC harmonic voltage measurement. On the other hand, the DC electrical measurement with sweeping the magnetic field allows us to quantify the DMI in the films possessing PMA.

In the first part, the SOT in Pt/GdFeCo with varying ambient temperature was investigated. GdFeCo is a ferrimagnet which possess magnetization compensation temperature, giving rise to the no net magnetization. The SOT in this bilayers system is driven by the spin Hall effect from the bottom Pt layer. A rapid increase of SOT around T_{M} is observed. In the framework of the conventional spin torque theory, spin orbit effective field should be inversely proportional to the net magnetization of GdFeCo. The results therefore could suggest that the reduction of the net magnetization of GdFeCo is the main factor of the SOT increase. It turns out that the damping-like torque efficiency simply scales with the total magnetization and is constant at all experimental temperature range.

The second and the third chapters were dedicated to investigate SOT and DMI in inversion asymmetric artificial superlattices (ABC-type) system. The superlattices with three different elements were expected to exhibit various spin-orbit phenomena due to the lack of inversion asymmetry in the whole structure.

In the second chapter, SOT in non-centrosymmetric [Pt/Co/W]-SL was studied. In this SL, two different crystal structures [face-centered cubic Pt and A15 structured BCC-W(] composed of few atomic monolayers are in contact with 6 Å FCC Co layers, giving ri se to a fully broken inversion symmetry for the whole structure. We demonstrated that the both DL and FL torque increase with W thickness up to 0.6 nm and have maximum at this specific thickness. The maximum charge-to-spin conversion efficiency in [Pt/Co/W(0.6)]-SL is calculated as ~ 0.42 for the DL-SOT and ~ 0.59 for the FL-SOT, respectively. It turns out that the spin Hall angle in the inversion asymmetric superlattice is larger than that of symmetric case (i.e., [Pt/Co]-SL). When the Pt thickness varies in [Pt/Co/W(0.6)]-SL, the both torques are dropped at 2 nm of Pt thickness. The change of the SOT with the thickness variation in W and Pt cannot be explained by the bulk spin Hall effect.

On the other hand, the XRD gave us a clue about the change of SOT in the artificial superlattices. When the W thickness is varied, the Pt/Co (111) crystallinity deduced from the intensity of Pt/Co (111) peak has a maximum at W(0.6). The trend of crystallinity at the Pt/Co interface observed in [Pt/Co/W]-SL coincides with that of effective spin Hall angle. Moreover, the out-of-plane strain relaxation at the Pt/Co interface is observed when the Pt thickness increases more than 1 nm. This strain relaxation in the out-of-plane direction also matches with the sudden diminished SOT in [Pt(2)/Co/W]-SL. Therefore, we can conclude that Pt/Co (111) crystallinity and the accumulated strain due to the different lattice parameter of Pt and Co increase the SOT in [Pt/Co/W]-SL. Therefore, it clearly shows that the interface properties affect to the magnitude of SOT which implies that the improved SOT in the inversion asymmetric superlattice can originate from the Rashba-Edelstein effect rather than the bulk spin Hall effect.

The relation between the orbital moment and SOT is studied by utilizing XMCD spectra. The XMCD spectra measured at two distinct angles (0º and 70º) allows us to quantify the orbital moment to the effective spin moment. It is found that the anisotropic orbital hybridization occurs in the [Pt/Co/W]-SL. The 0.6 nm of W insertion maximizes orbital hybridization in the perpendicular direction. The trend of perpendicular orbital hybridization matches with that of SOT. The perpendicular orbital moment and the FL-SOT which is known as the main contribution from the Rashba-Edelstein effect are scaled. It is found out that there is a positive relation between FL-SOT and perpendicular orbital moment. On the other hand, the deviation of [Pt/Co]-SL from the positive relation indicates that Pt/Co and Co/Pt interfaces are distinct. Thus, we concluded that the SOT enhancement in non-centrosymmetric [Pt/Co/W]-SL is caused by the anisotropic orbital hybridization resulting in improving Rashba-Edelstein effect through asymmetric electronic structure at the interface.

In the third chapter, the relation between DMI and PMA was studied in the SL with and without inversion symmetry, in the [Co/Pt], [Co/Pd], and [Co/Pd/Pt]-SL, respectively. In the series of SL, we change the various parameters in the SL, namely, the Co thickness, repetition numbers, and heavy metal thickness. As varying Co, the DMI energy (D) has a peak at the specific Co thickness where the interfacial anisotropy energy (K_S) starts to be saturated. The DMI is larger in the sample possessing inversion asymmetry which is consistent with the previous studies. However, the DMI is sizable even in the symmetric samples, implying that the two interfaces are not identical in the symmetric superlattices. It is found that the K_S and D have a positive relation, suggesting the K_S and D share the same origin.

In cases of increasing repetition numbers and heavy metal thickness, both the D and effective anisotropy energy (K_{eff}) are enhanced. Moreover, the D and the K_{eff} are turned out to have a positive proportionality in both cases. The positive proportionality may come from the superimposing of the interface effects when the repetition numbers increase. For varying the heavy metal thickness, the increase is possibly due to the enhancement of the SOC which is the mainly associated with the DMI energy and anisotropy energy.

（続紙　２　）

（論文審査の結果の要旨）

　本論文は、反転対称性の破れた磁性多層膜における、スピン軌道トルクやジャロシンスキー・守谷相互作用に着目した研究を行っており、「Pt/GdFeCo二層膜におけるスピン—軌道有効磁場の温度依存性」、「中心対称性のない人工格子における電流スピン変換」、「[Co/Pt]、[Co/Pd]、[Co/Pd/Pt]の人工格子におけるジャロシンスキー・守谷相互作用」の３つの内容で構成されている。

　「Pt/GdFeCo二層膜におけるスピン—軌道有効磁場の温度依存性」では、Pt/GdFeCoにおけるスピン軌道トルクの温度依存性を調査した。フェリ磁性体であるGdFeCoは、正味の磁化が０となる磁化補償温度を有する。スピン軌道トルク由来の有効磁場を測定した結果、磁化補償温度付近で急激に増大することが分かった。スピン軌道有効磁場はGdFeCoの正味の磁化に反比例することから、GdFeCoにおける電流からスピン流への変換効率は温度に対して一定であることを意味している。

　「中心対称性のない人工格子における電流スピン変換」では、反転非対称の破れた[Pt/Co/W]人工格子におけるスピン軌道トルクについて調査した。電流-スピン流変換効率をWの膜厚を変化させて測定した結果、0.6 nmで最大になることがわかった。同一の試料における磁気円二色性測定から、スピン軌道トルクの増大と軌道混成に相関があることを示した。一方、Ptの厚さを変化させた場合、電流-スピン流変換効率が2 nmで減少することがわかった。X線回折の結果、Pt/Co(111)の面間における垂直方向の応力の変化がスピン軌道トルクの傾向と一致していることが明らかになった。本結果は、軌道混成の制御により、スピン軌道トルクの増大が可能であることを意味している。

　「[Co/Pt]、[Co/Pd]、[Co/Pd/Pt]の人工格子におけるジャロシンスキー・守谷相互作用」では、 [Co/Pt]、[Co/Pd]、[Co/Pd/Pt]の三種類の人工格子における磁気異方性と、ジャロシンスキー・守谷相互作用（DMI）との関係を調査した。本試料では各層の膜厚および、積層回数を変化させた。初めに、Coの厚さを変化させると、ジャロシンスキー・守谷相互作用のエネルギー（D）は、界面磁気異方性エネルギー（K_S）が飽和し始める膜厚でピークを持つことが分かった。K_SとDは比例関係を有しており、両者は同じ起源を共有することを意味している。また、[Co/Pd/Pt]の超格子におけるDMIは [Co/Pt]や[Co/Pd]より大きいことを確認した。これは、Pt(Pd)/CoとCo/Pt(Pd)界面が同一ではないことを示唆している。

　次に、積層回数と重金属の厚さを増やすと、Dと磁気異方性エネルギー（K_{eff}）が共に増加し、両者は比例することが分かった。本実験結果は、人工格子の構造を変化させることで、DMIと磁気異方性を制御できることを意味している。

　よって、本論文は博士（理学）の学位論文として価値あるものと認める。また、平成３１年１月１８日、論文内容とそれに関連した事項について試問を行った結果、合格と認めた。

要旨公表可能日：　　　　　　年　　　月　　　日以降